Remote Sensing of Subsurface Biomineralization

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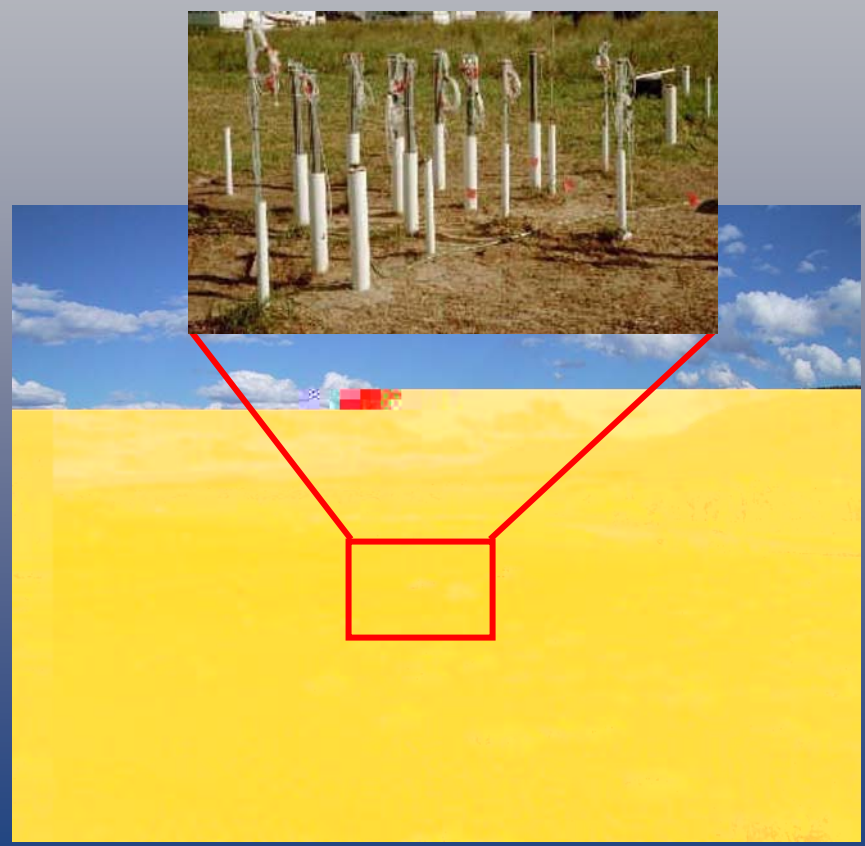
Motivation

"Use of non-invasive geophysical methods to monitor the extent and stability of biomineralization products ***over large spatial scales***"

- ***Hypothesis***: microbial processes induce ***changes in mineralogy*** that can be detected using time-lapse induced polarization methods
- ***Challenges***:
  - Competing metabolic processes
  - Mineral phase transformations
  - Non-contaminant mineral effects
  - Poor signal contrast

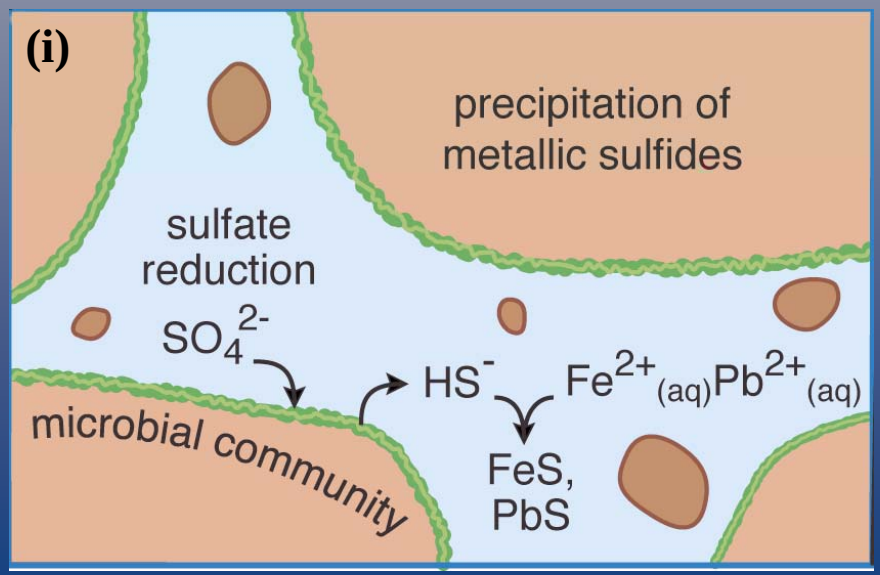


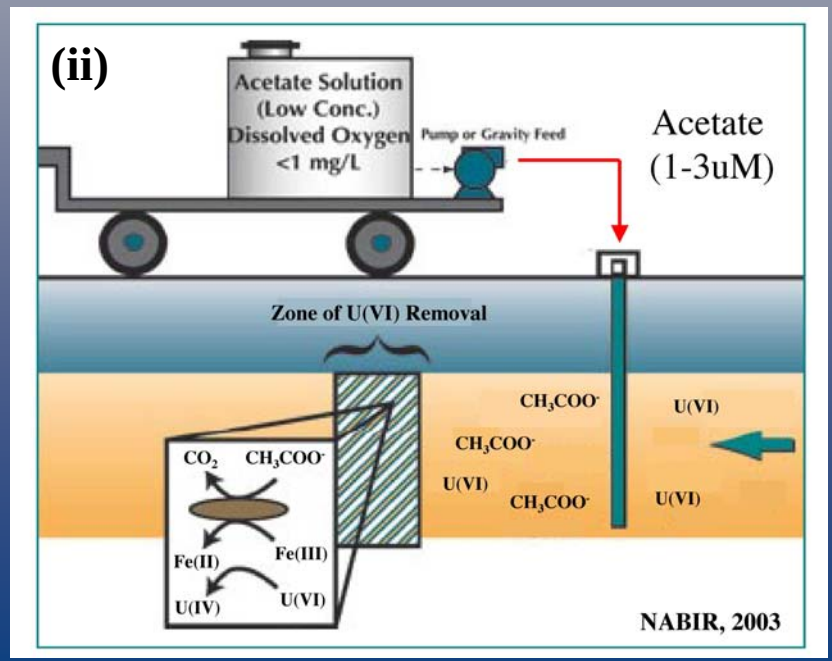
Stimulated Biomineralization

- Use of indigenous microorganisms to remediate toxic metals and radionuclides in groundwater
  - Delivery of substrates necessary to promote desired metabolism
  - Conversion from ***soluble*** to ***insoluble*** forms:

(i) Pb^{2+}, Zn^{2+} (aq) + $H_2S \rightarrow$ PbS, ZnS (s) + $2H^+$ [via SO_4^{2-}-reduction]

(ii) U^{6+}, Cr^{6+} (aq), $\rightarrow$ UO_2, Cr_2O_3 (s) [via Fe(III)-reduction]





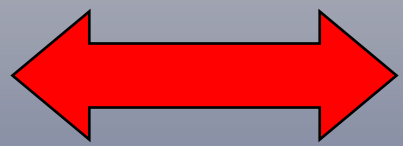
Geophysical Monitoring:

Possibilities and Pitfalls

Successful interpretation requires an understanding of…

Mineralogy

(e.g. aggregation state, phase, etc.)

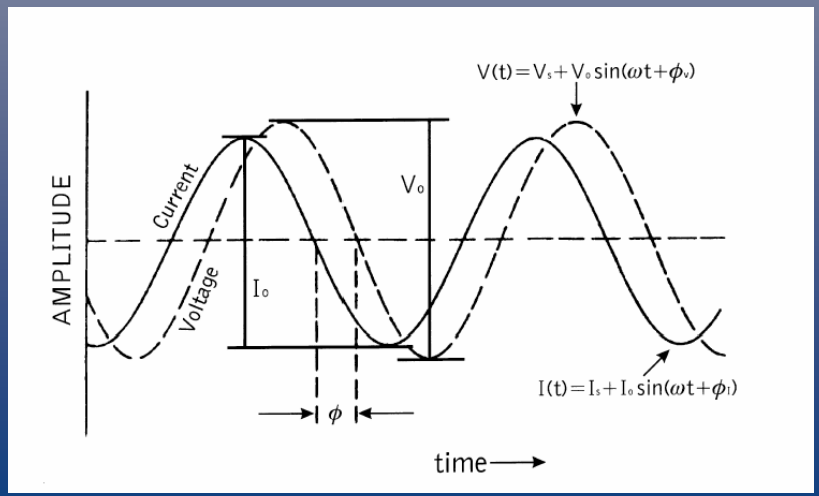


Metabolism

(e.g. Fe- vs. SO_4-reduction)

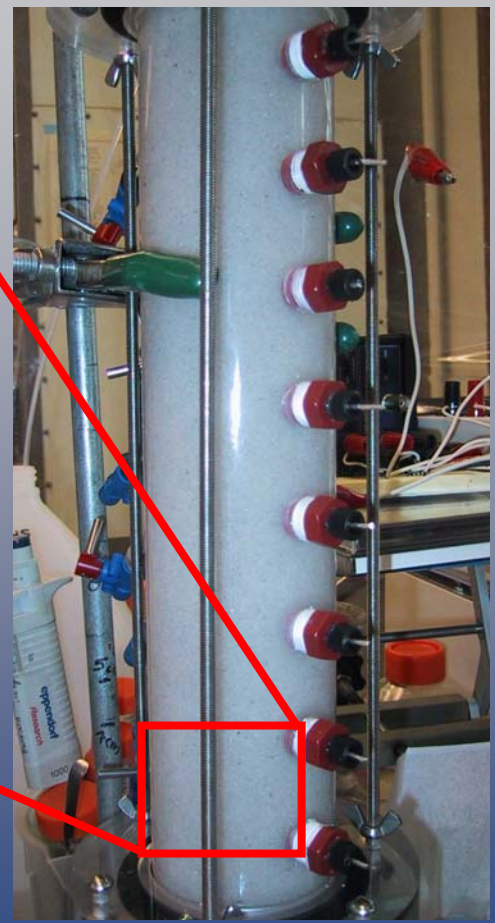
Lab Measurements of Microbe-Induced ZnS and FeS Precipitation

- ***Spectral Induced Polarization***
  - Low frequency (0.1-1000 Hz) electrical measurements
  - Measure ϕ and |Z|
  - Correlate changes with:
    - Active SRB metabolism
    - ZnS, FeS precipitates
    - ***Aggregation state, texture, and composition of precipitates***



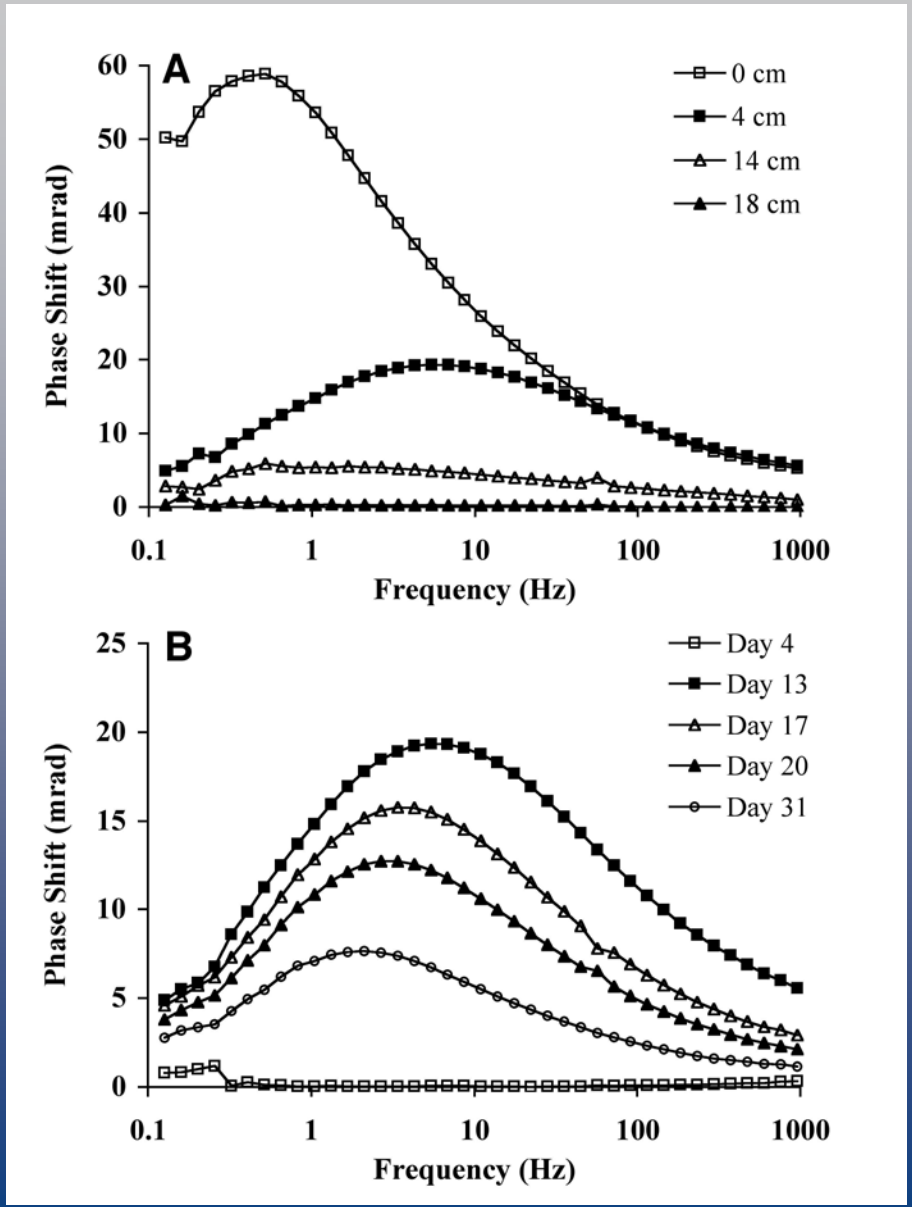
baseline

31 days



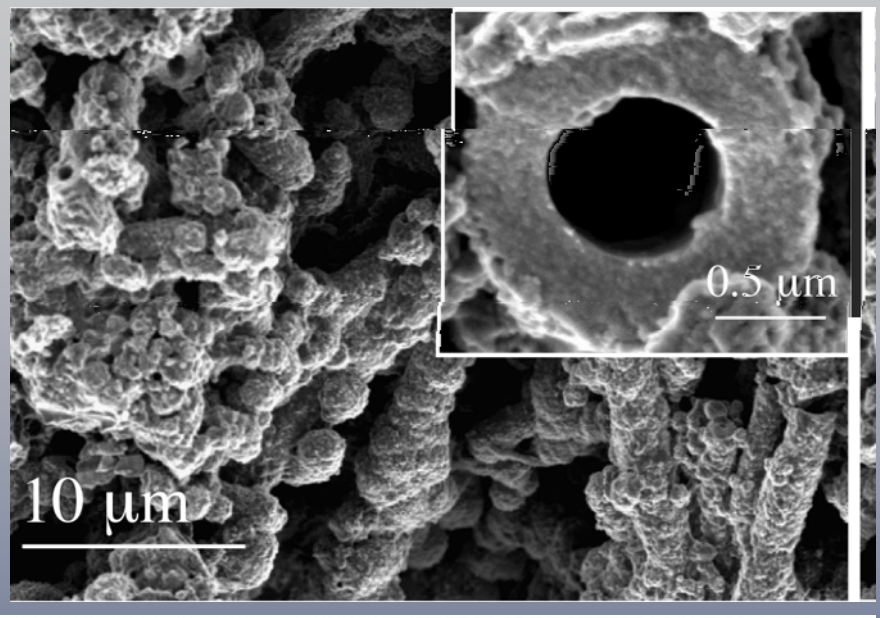
Lab Measurements of Microbe-Induced ZnS and FeS Precipitation

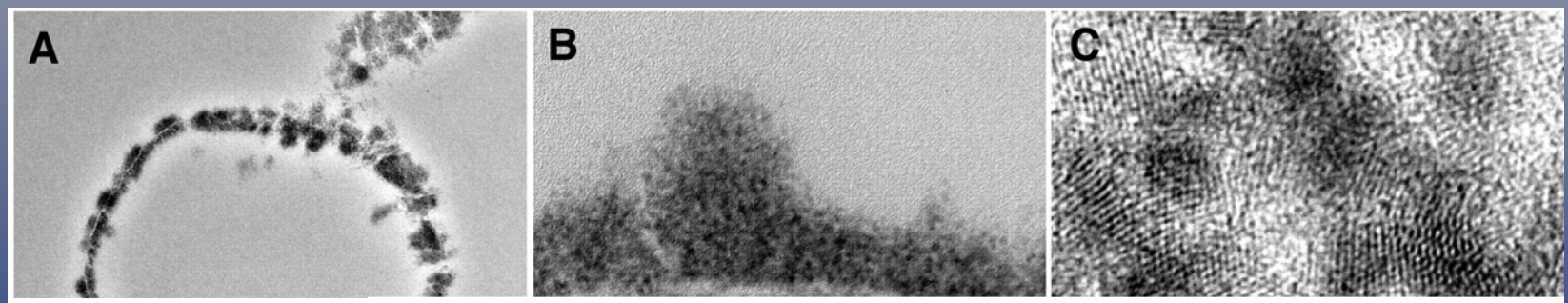
- ***Induced Polarization Results***
  - Phase shifts are spatially variable (**A**)
    - ***Motility due to chemotaxis***
  - Phase shifts are temporally variable at a given location (**B**)
    - ***Mineralogical effects:***
      - Aggregation of nano-particulate precipitates
      - Crystal growth and ageing



Lab Measurements of Microbe-Induced ZnS and FeS Precipitation

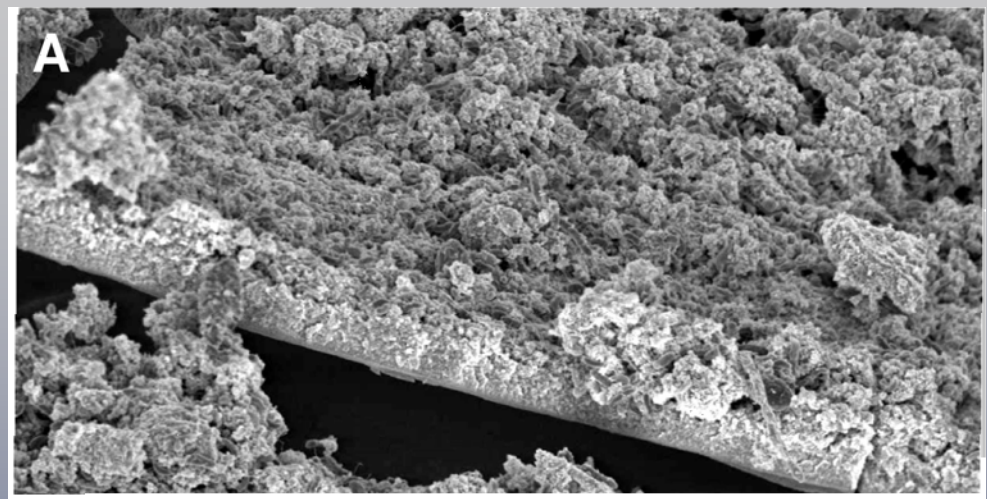
- ***Mineral evolution (1):***
  - Sulfides are initially nano-particulate and tied to cell surfaces
  - Characteristic of biogenic precipitates
    - ***Large surface areas***
    - ***Large phase shifts***



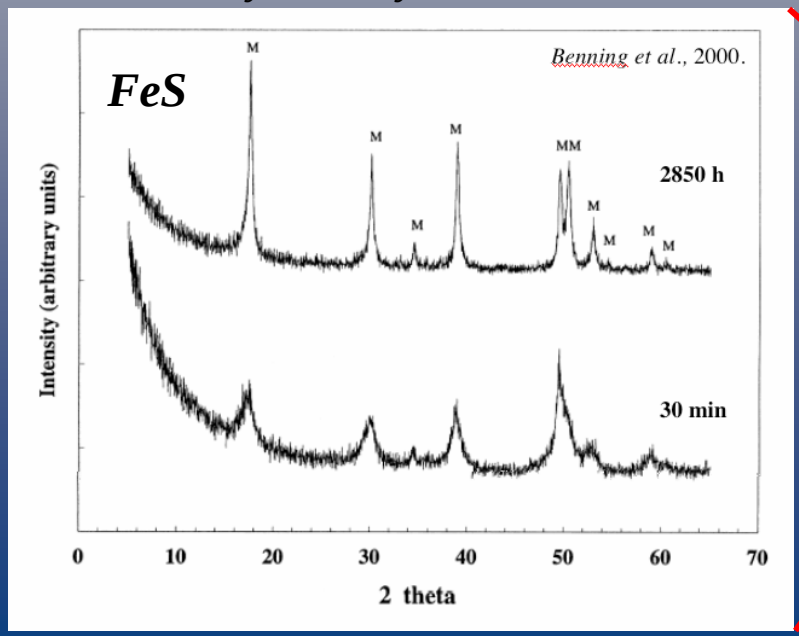


Lab Measurements of Microbe-Induced ZnS and FeS Precipitation

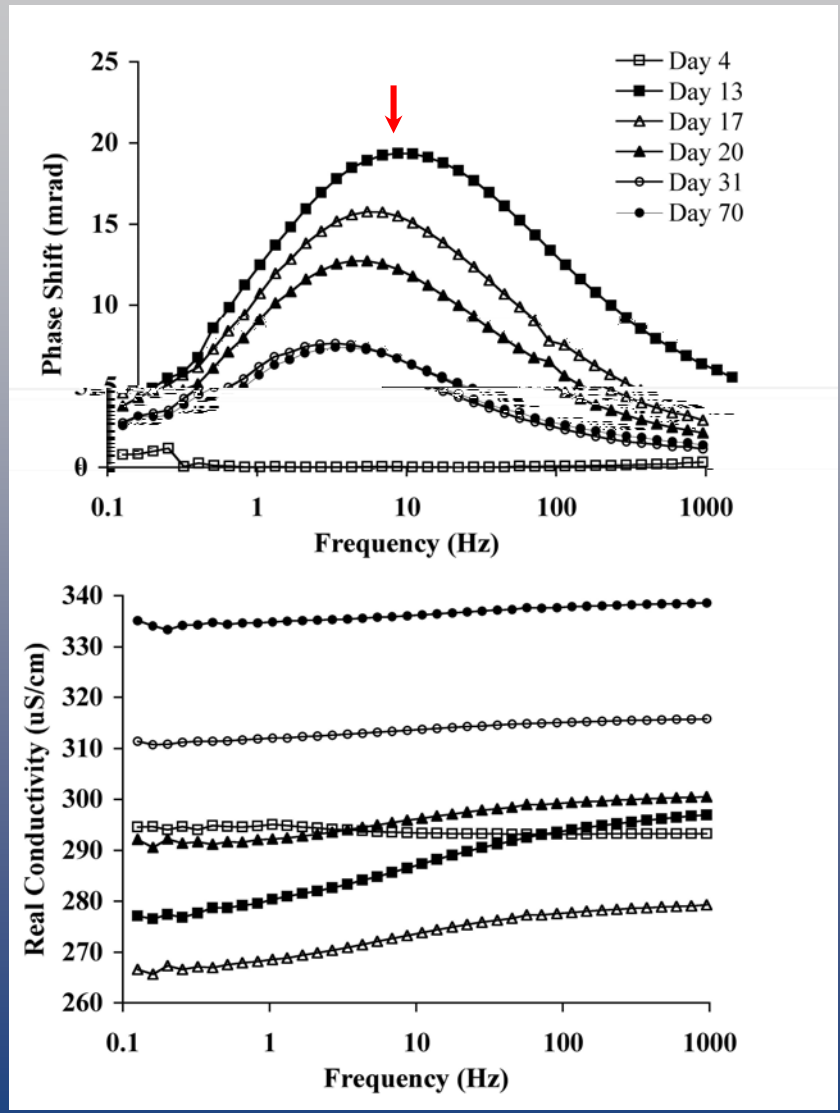
- ***Mineral evolution (2):***
  - Overlain by non sulfide-encrusted cells (**A**)
  - Aged FeS coats grain surfaces
    - ***Dense, crystalline FeS layer*** (**B**)
    - ***Platy crystal habit*** (**C**)



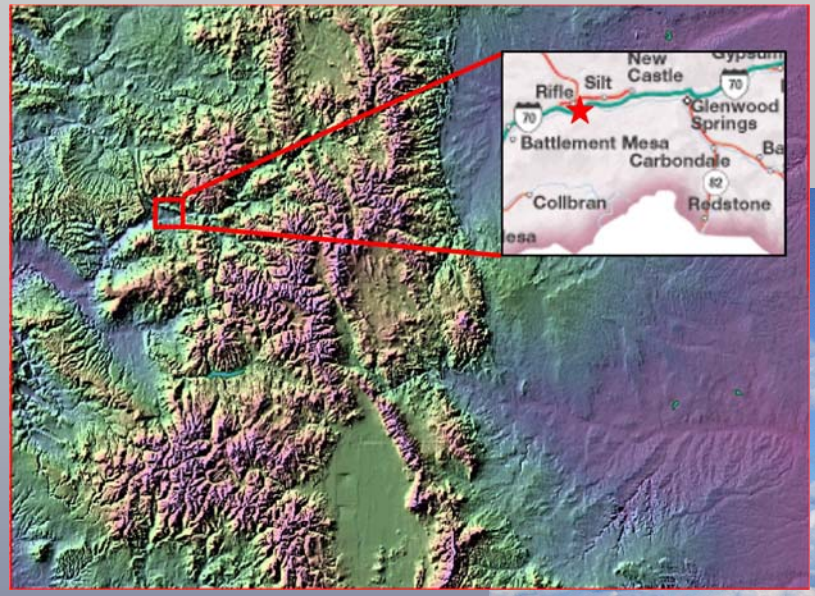
XRD analysis indicates increasing crystallinity with time



Lab Measurements of Microbe-Induced ZnS and FeS Precipitationcon



Field Monitoring: U(VI) Remediation at Old Rifle Site, CO



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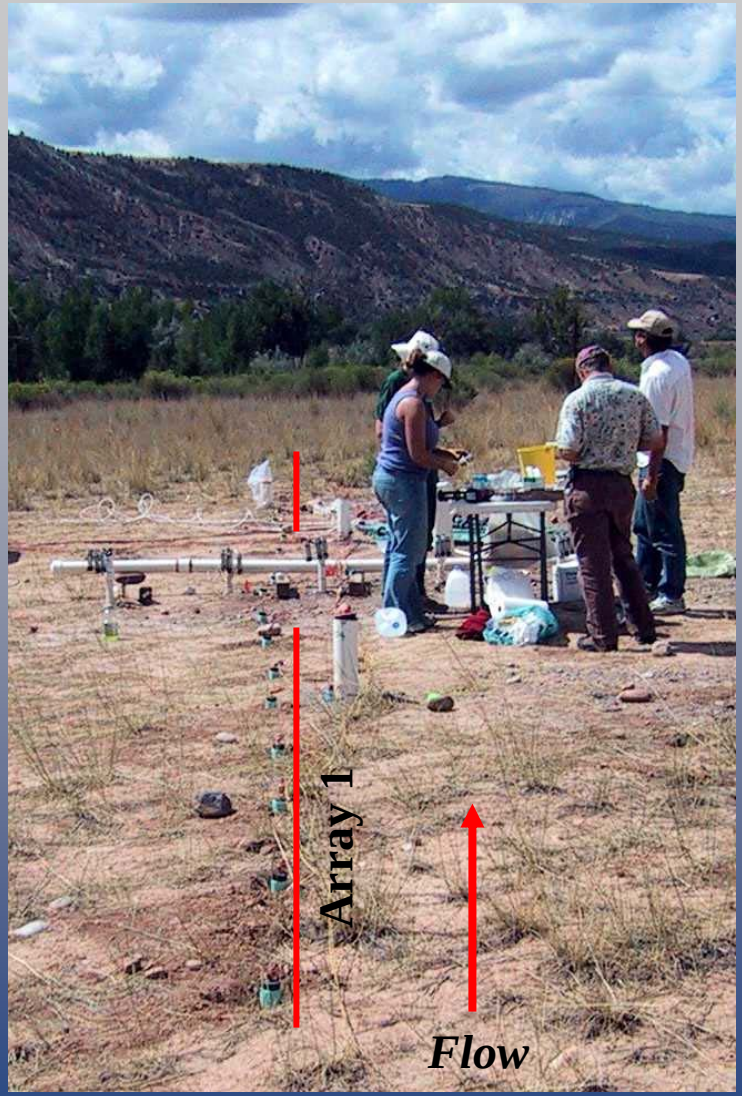
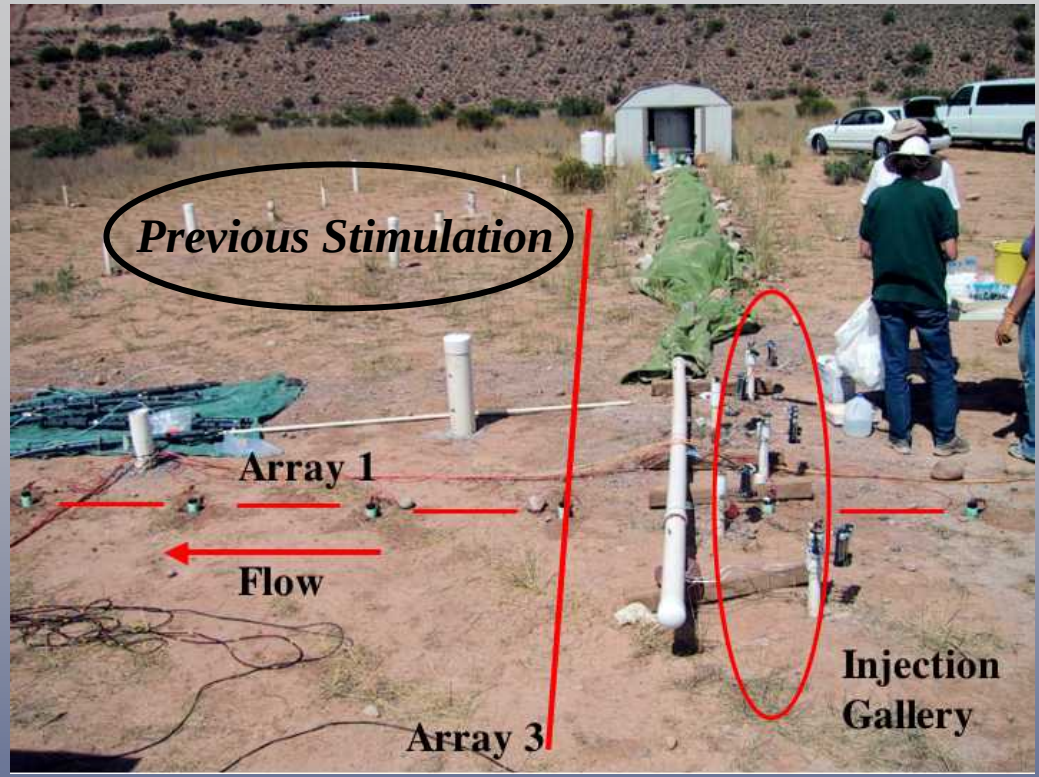
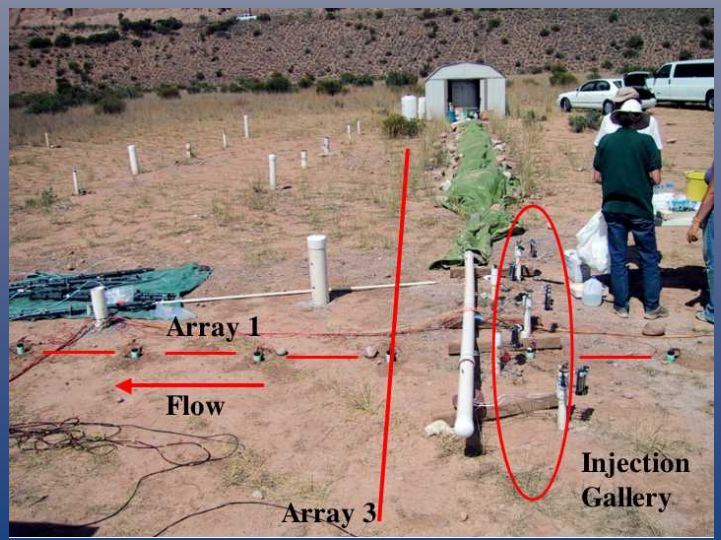


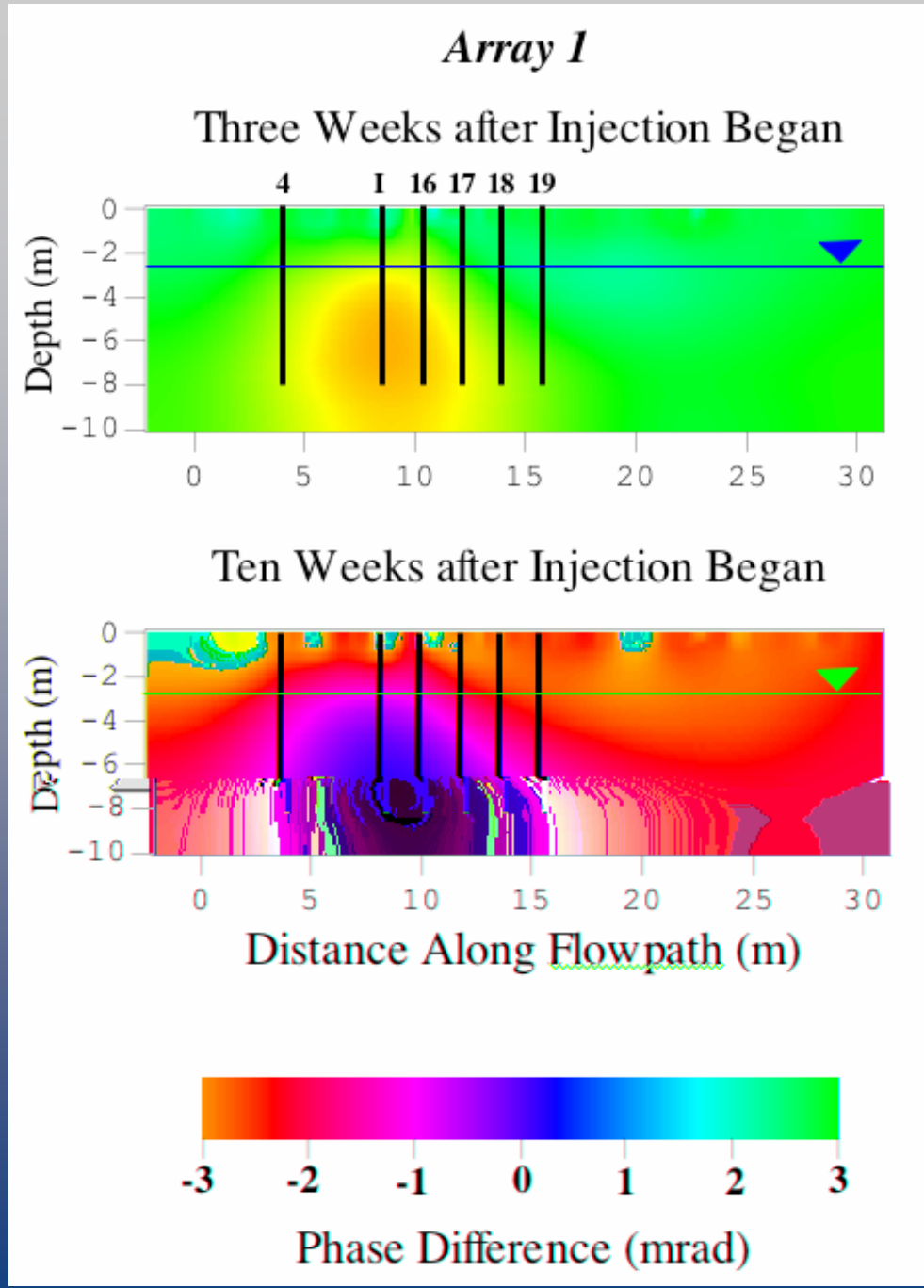


- ***Surface Spectral IP Survey:***
  - Zonge GDP-32 RPIP survey
    - ***0.125, 1, and 8 Hz***
  - Electrode spacing: 1.0 m
  - Dipole-Dipole survey w/ 4.0 m dipole
  - $Cu/CuSO_4$ electrodes

Array 1: Parallel to flow

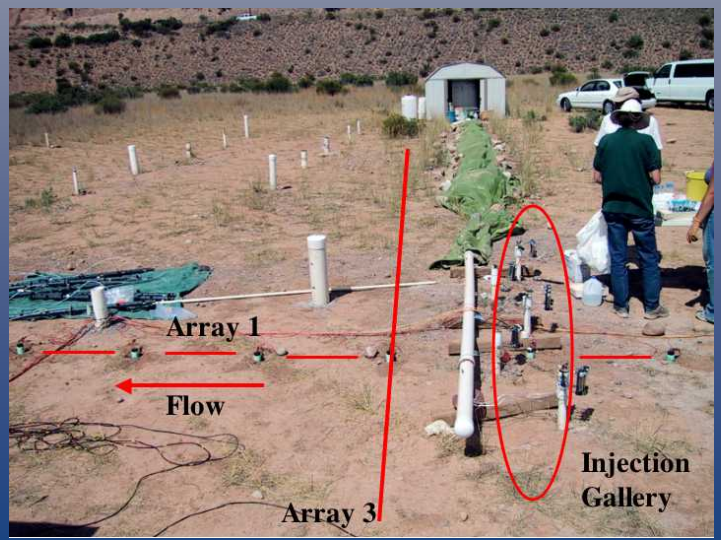
- ***Time-lapse IP results (*0.125 Hz*)*:**
  - Phase shifts ***decrease*** w/time
  - Changes occur:
    - ***Below water table***
    - ***Near injection wells (I)***
      - *Some upgradient effects*

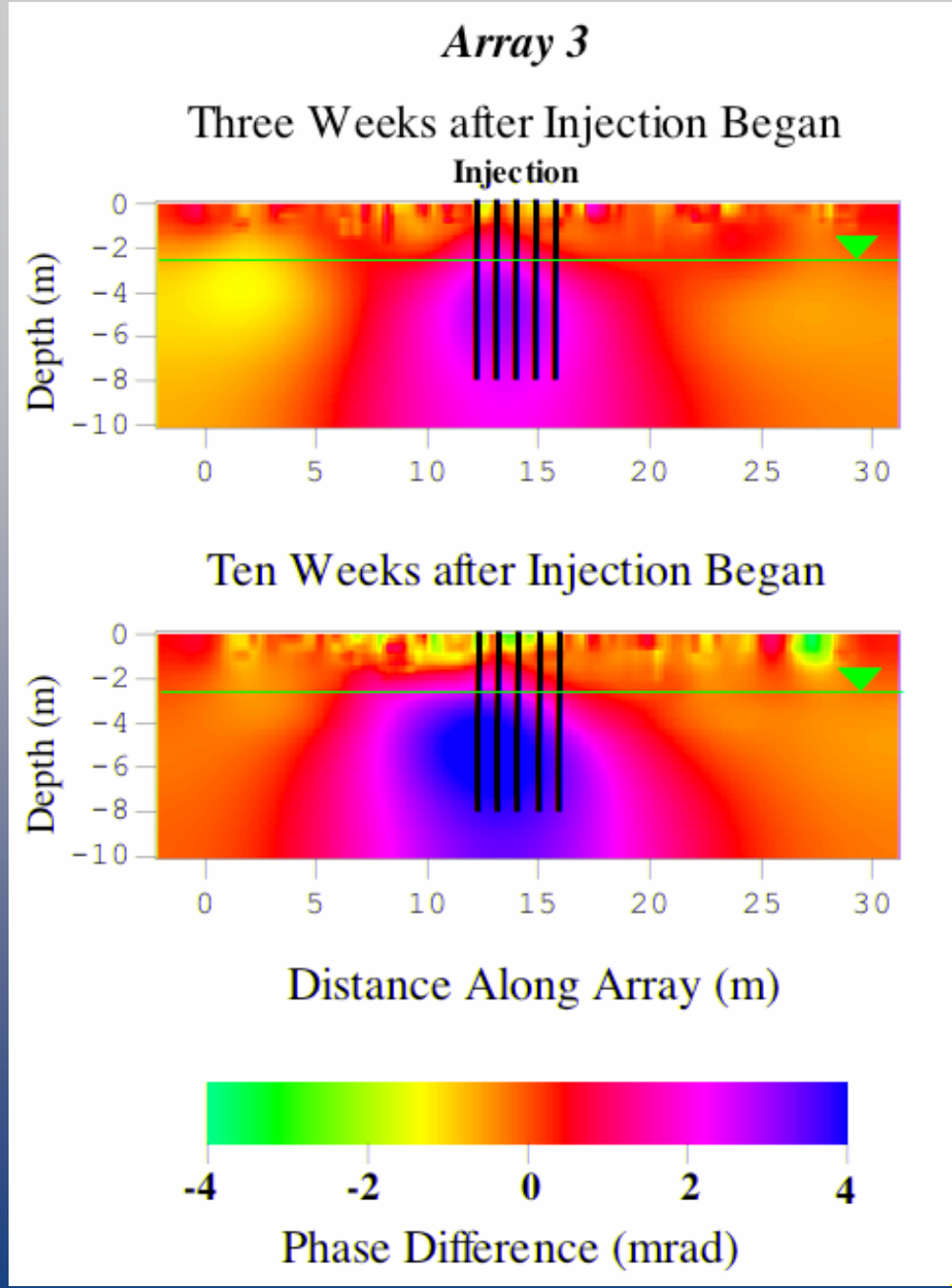




Array 3: Perpendicular to flow

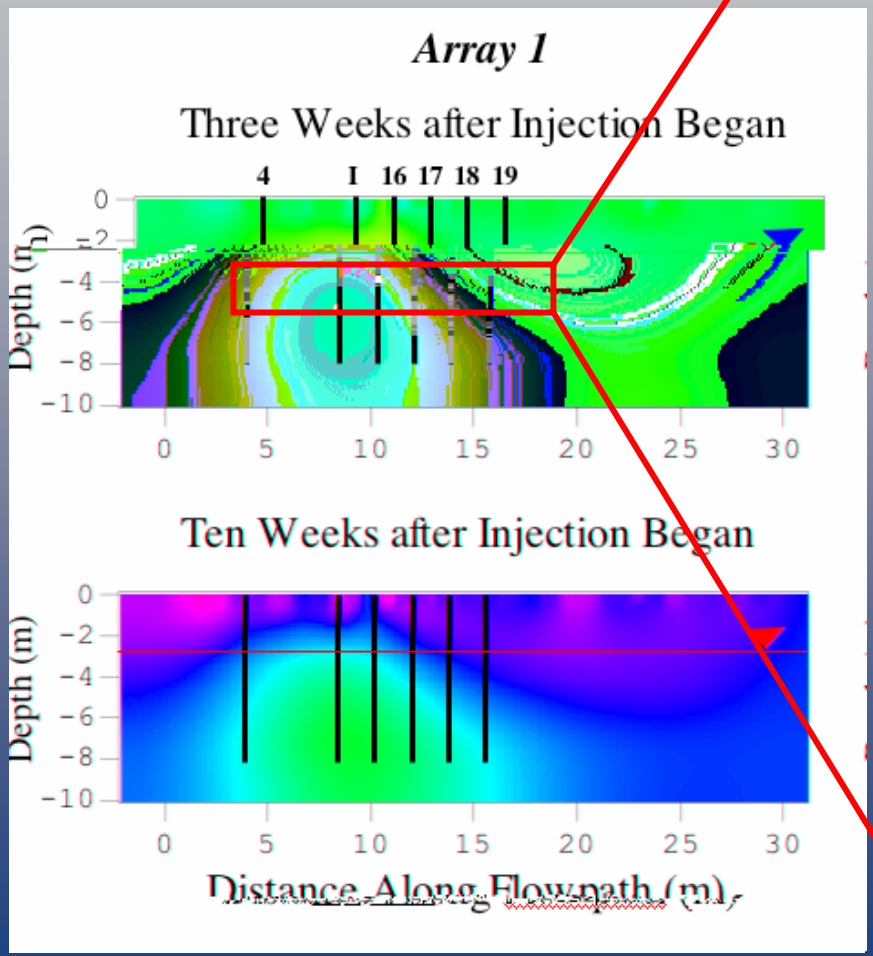
- ***Time-lapse IP results (*0.125 Hz*)*:**
  - Phase shifts ***decrease*** w/time
  - Changes occur:
    - ***Below water table***
    - ***Near injection wells (I)***
      - *Lateral effects*

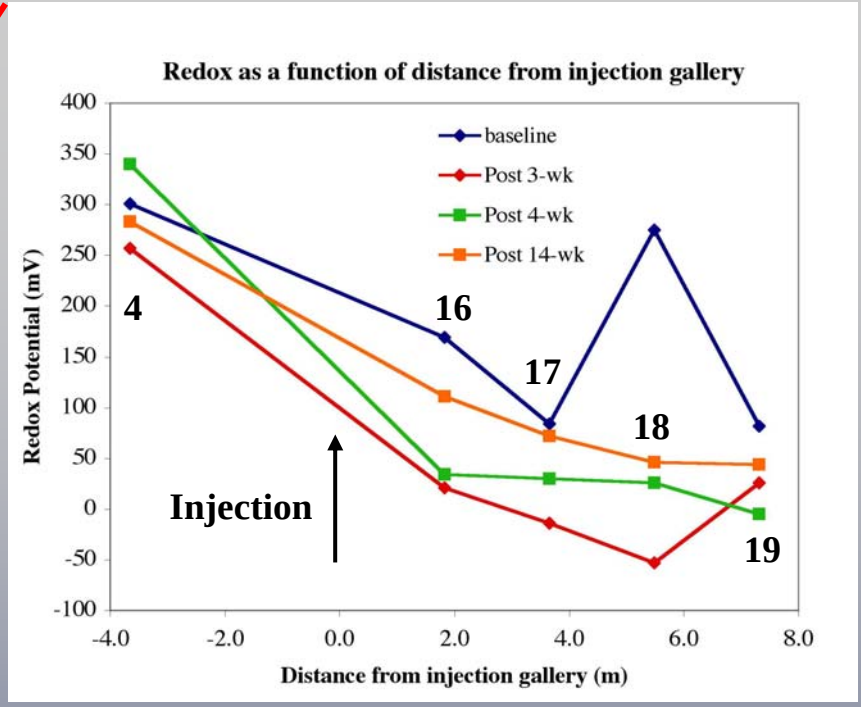


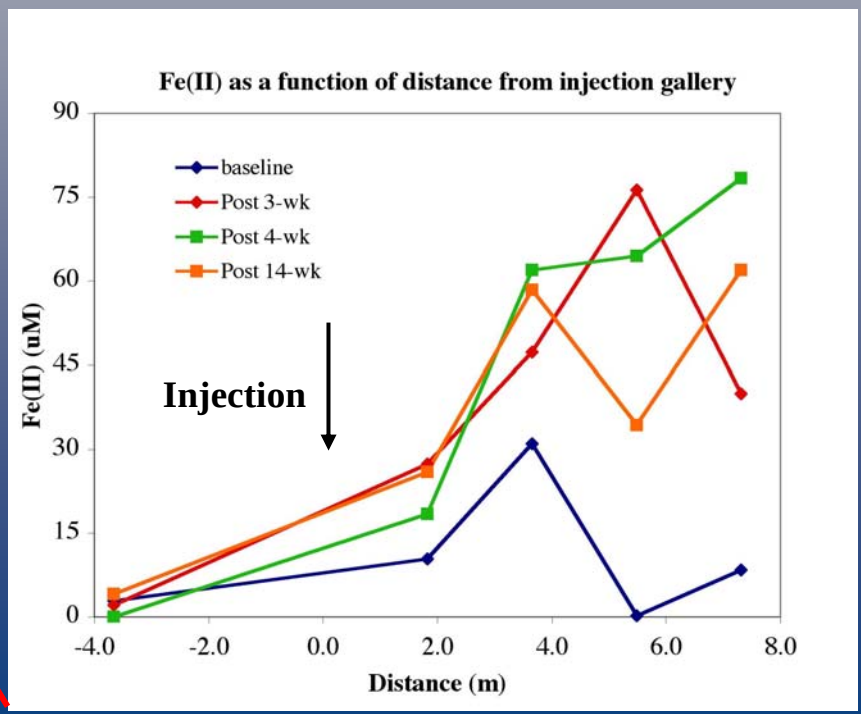


Geochemical Results

- ***Stimulated Fe(III)-reduction:***
  - Decreasing Redox potentials
    - ***Fe(III)/Fe(II): 100 to -100mV***
  - Increasing Fe^{2+} concentrations

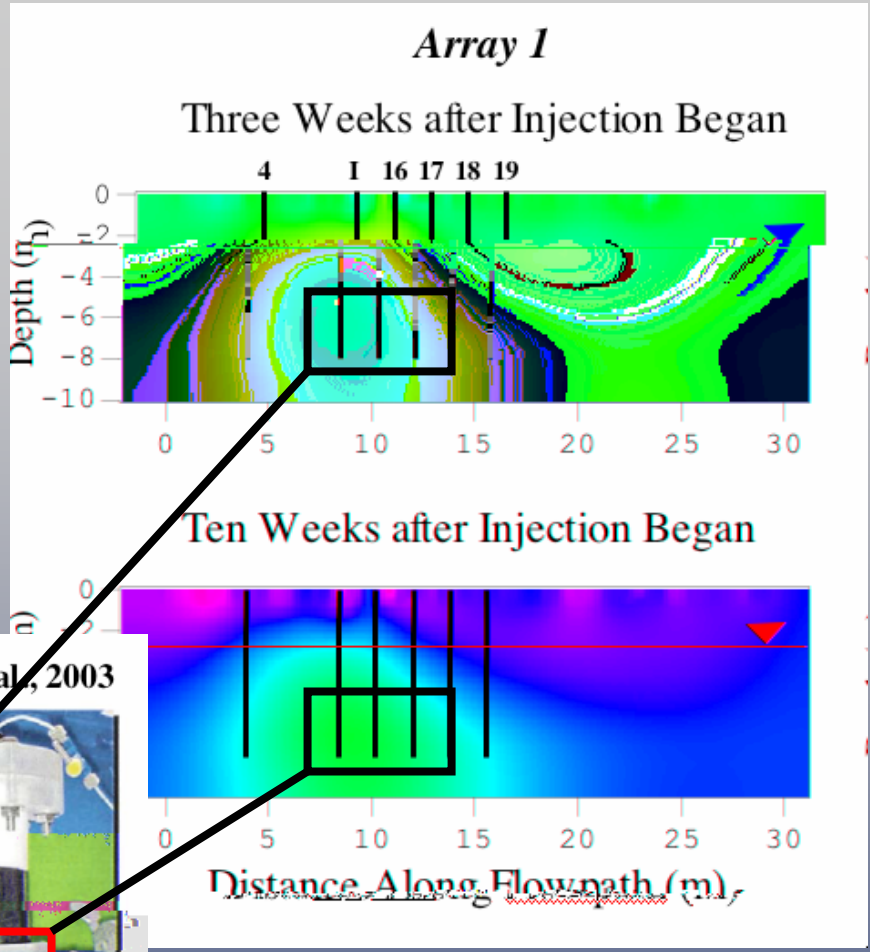


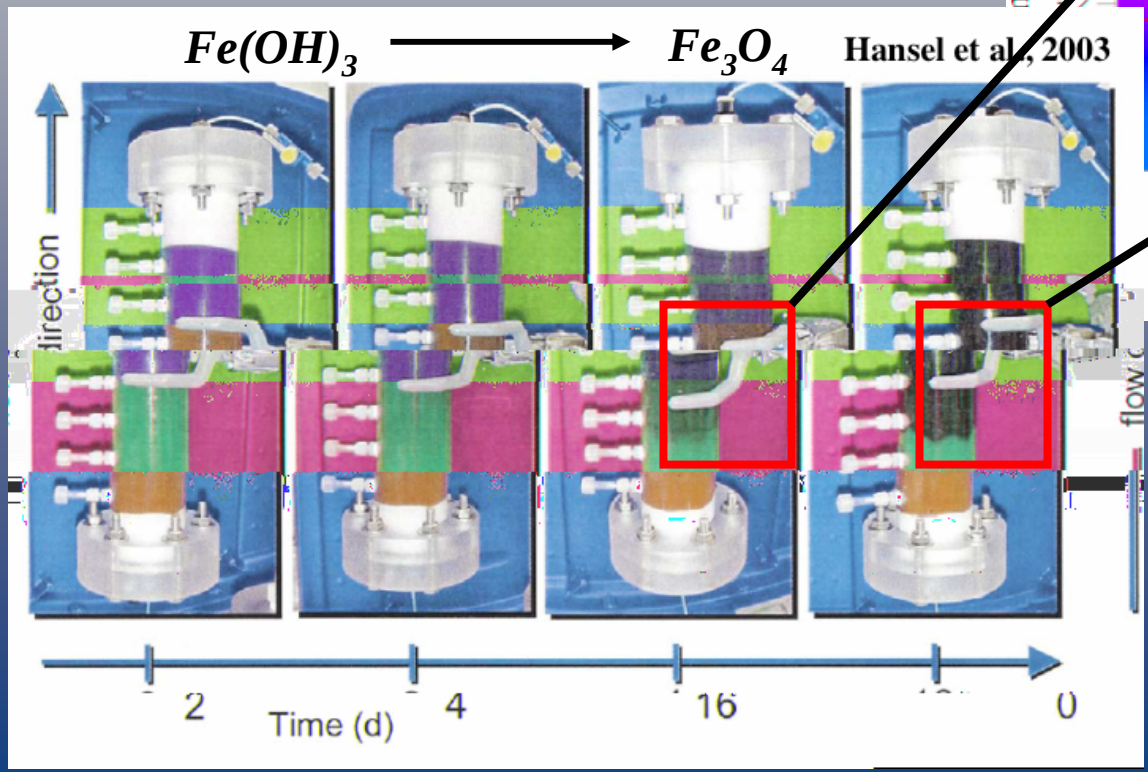




Proposed IP Mechanism

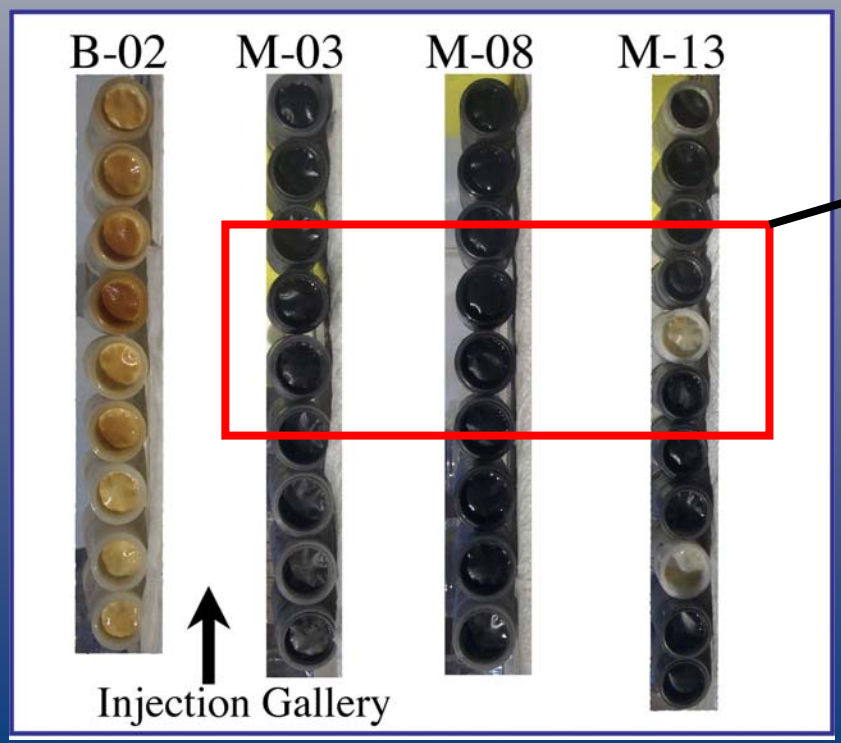
- ***Stimulated Fe^{3+}-reduction:***
  - Mineralogical changes
    - $Fe(OH)_3 \rightarrow FeOOH \rightarrow Fe_3O_4$
    - Decreasing surface area
    - Creation of less polarizable phases (e.g. magnetite)

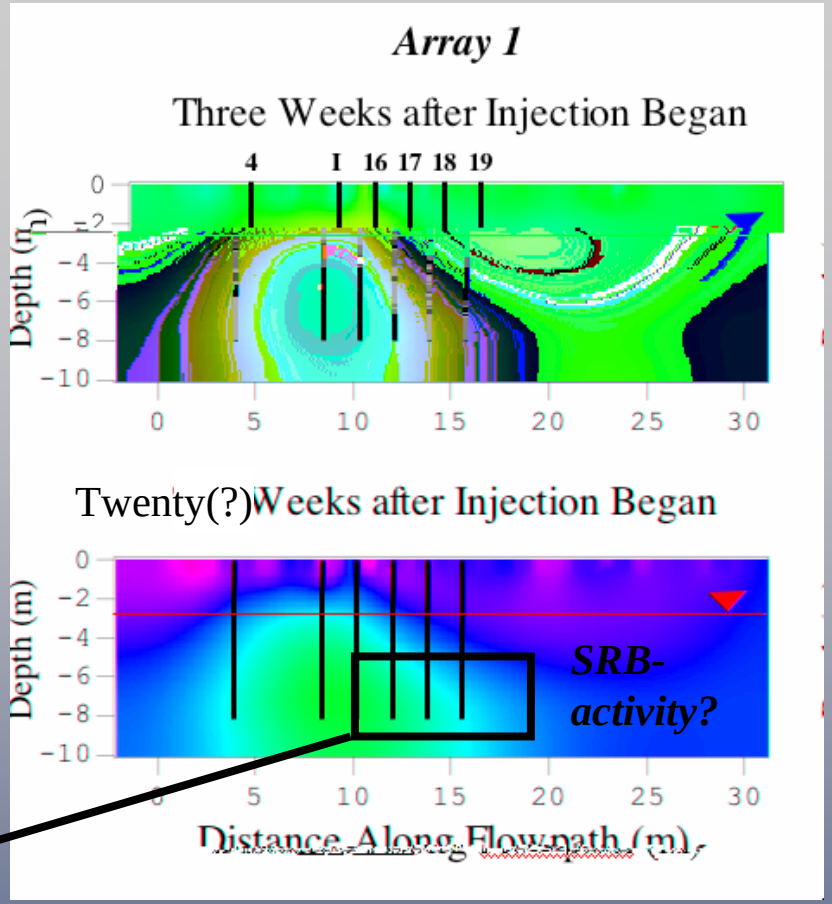


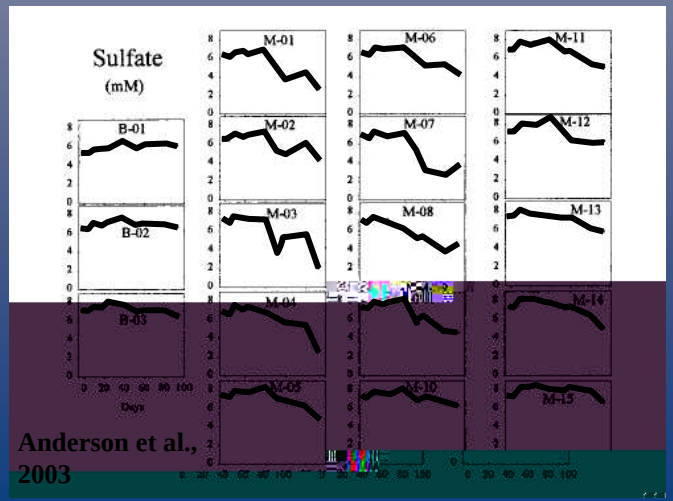


What's Next and Why?

- ***Transition to sulfate-reduction:***
  - **Correlates w/ rebound in U(VI)**
  - FeS observed during previous experiment (still occurring!)
    - Creation of ***polarizable*** phases
- ***Multiple metabolic pathways***
  - Distinct IP signals for both!







Summary

Improved understanding of geophysical observations:

- Processes that ***influence*** contaminant metals remediation during biostimulation
  - ***Understanding mineralogical effects is critical***
- Potential of using ***IP method*** as a minimally invasive ***field-scale*** approach for monitoring such processes
  - ***Understanding metabolic effects is critical***

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